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FIR emission and absorption due to indirect optical transitions of hot electrons in GaAs/AlGaAs QW

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Abstract. Far-infrared ($\lambda = 70\ldots300\,\mu$m) spontaneous emission and modulation of absorption under heating 2D-electrons in strong electric field applied along GaAs/AlGaAs quantum layers are observed and investigated. Emission and absorption of light are connected with indirect transitions of hot electrons in ground subband of quantum well. Hot electron temperature is determined from comparing experimental emission spectra and theoretical ones taking into account optical phonon, impurity and interface roughness scattering as well as electron-electron scattering.

Introduction

Intraband electron and hole transitions are intensively studied during last years. Partly, it is connected with development of fast photodetectors and modulators of infrared (IR) range. The creation of quantum cascade [1] and fountain [2] lasers gave impetus to this line of physics of low-dimensional systems. The main part of the works on the optical intraband phenomena is devoted to absorption and emission of radiation due to direct transitions of electrons between subbands. For example, emission of FIR connected with intersubband direct transitions of electrons and holes is studied in [3, 4, 5]. However light emission and absorption caused by intrasubband transitions of hot carriers has not yet investigated. In the meantime these phenomena accompany emission and absorption due to direct optical transition and can serve as a source of information about carrier properties.

The aim of the present paper was to find and experimentally and theoretically investigate spontaneous FIR emission and modulation of FIR absorption under electron heating from GaAs/AlGaAs multiple quantum well structures.

1 Calculation of emission spectra

We consider simple rectangular selectively doped in the barrier quantum wells with one or more (for example, two) levels ε_1 and ε_2 of size quantization. If the distance between levels $\Delta\varepsilon = \varepsilon_2 - \varepsilon_1$ is rather great then the absorption and emission of far-infrared light ($h\nu \ll \Delta\varepsilon$) with polarization $\mathbf{e}_\omega \perp OZ$ (OZ is structure growth direction) can occur only due to indirect transitions of electrons within ground subband $\varepsilon_1(k_\parallel)$. The momentum conservation is provided due to processes of electron scattering. One can distinguish optical phonon, impurity, interface roughness as well as e-e scattering. It should be noted that the light polarized along the structure ($\mathbf{e}_\omega \parallel OZ$) can be absorbed

only using virtual states in the second subband $\varepsilon_2(k_{||})$ but calculations shows that the contribution of such transitions to the absorption is relatively small and we will not take them into account.

We calculated spectral density of emitted photons as

$$\frac{\mathrm{d}N}{\mathrm{d}\omega} = \rho_\omega W^{em} = \rho_\omega \sum_{\mathbf{k}'} \sum_{\mathbf{k}} w(\mathbf{k}, \mathbf{k}') f_{\mathbf{k}}(1 - f_{\mathbf{k}'}), \qquad (1)$$

where wave vectors $\mathbf{k}$ and $\mathbf{k}'$ describe initial and final states of electron during light absorption, $\rho_\omega = 2n^3\omega^2/\pi c^3$ is photon density of states, n is refraction index, c is velocity of light, $w(\mathbf{k}, \mathbf{k}')$ is probability of quantum emission due to indirect transitions. Its value is determined in the second order of perturbation theory:

$$w(\mathbf{k}, \mathbf{k}') = \frac{2\pi}{\hbar} \left| \sum_i \frac{H^\omega H^s}{\varepsilon_0 - \varepsilon_i} \right|^2 \delta(\varepsilon_f - \varepsilon_0). \qquad (2)$$

Here ε_0, ε_i and ε_f are the energies of initial, intermediate and final states of system, H^ω is matrix element of energy of interaction between electron and light, H^s is matrix element of energy of interaction between electron and scattering center. We took into account electron interaction with optical phonons, impurities, interface roughness and e-e interaction. We used simplified method of calculating interface roughness scattering from [6]. The parameter of calculation was the concentration of scattering islands on GaAs/AlGaAs interface. It is shown that e-e interaction could result in absorption and emission of long wavelength light only if nonparabolicity of energy spectrum is took into account. Analytical expression of transition probabilities are obtained for non-degenerated and strongly degenerated electrons. Calculating spectral density accordingly (1) we used Fermi distribution function with electron temperature T_e.

2 The samples and experimental technique

We studied GaAs/$Al_{0.22}Ga_{0.78}As$ multiple quantum well structure consisted from 150 layers of QW of width 6 nm divided by doped 14 nm wide barriers. Spacer was 4 nm wide. The electron mobility at $T = 77$ K was 3300 cm^2/(Vs). The surface electron concentration $n_s = 3 \cdot 10^{11}\,\mathrm{cm}^{-2}$. The duration of pulses of longitudinal electric field was 200 ns. Experiment temperature was 4.2 K. Long wavelength radiation ($\lambda = 70\ldots300\mu$m) registered with Ge$\langle Ga\rangle$ photodetector. Radiation spectra were measured with the help of tuned InSb filter by magnetic field (see details in [7]). Far-infrared laser on hot holes in germanium was used to study modulation of light absorption coefficient in longitudinal electric field due to electron heating.

3 Results of experiment and calculations

The spontaneous emission spectra at different values of longitudinal electric field are presented in Fig. 1. Electron heating occurs with increase of electric field. It leads to increase of curve slopes. Results of calculations are presented in Fig. 2. The calculation of emission spectra took into account self-absorption processes. The consideration of spectral dependency of absorption coefficient introduces significant corrections to spectral density of radiation calculated from (1) (see inset in the Fig. 2). It should be

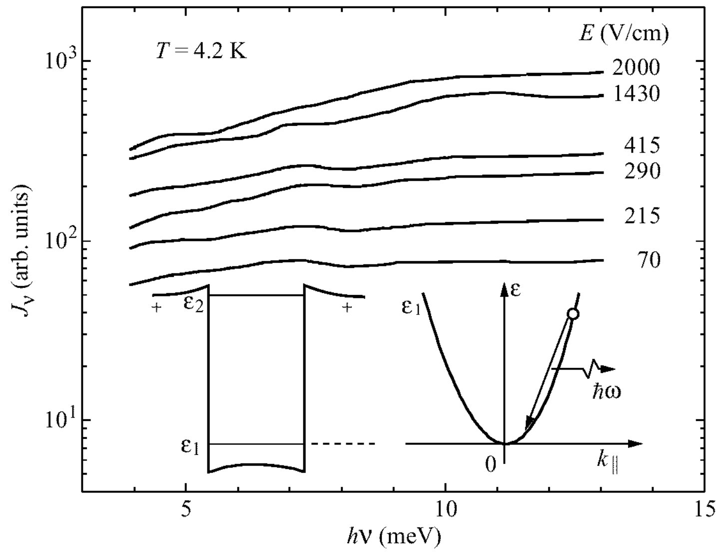

Fig 1. Experimental emission spectra.

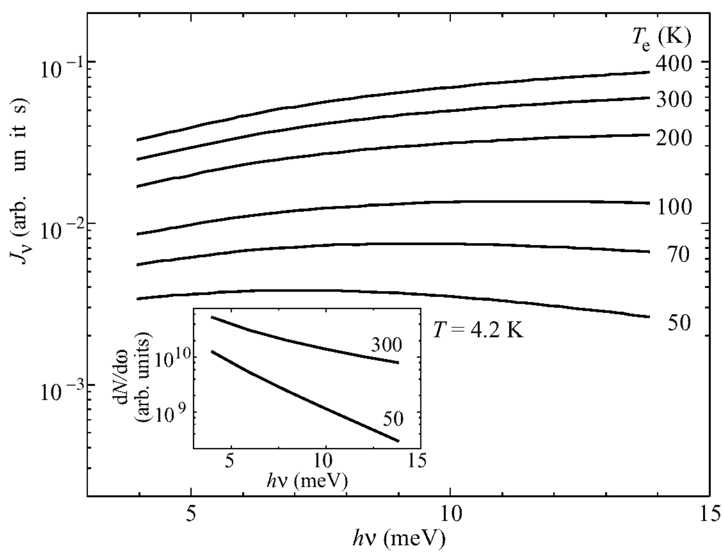

Fig 2. Calculated emission spectra. Spectra without considering self-absorption are presented in the insert.

noted that in different parts of spectra and at different values of electron temperature the relation between diverse scattering mechanisms is varied. So, at great electric field $E > 100$ V/cm the electron transitions with scattering on phonons and impurities contribute significantly to the spontaneous emission. Contribution of interface roughness and e-e scattering is substantially weaker.

A correlation between experimental and calculated emission spectra allowed us to obtain the electron temperature as a function of electric field. The electron temperature reaches 400 K at $E = 2$ kV/cm. Our results are agreed with data of [8] where similar radiation from single heterojunction at moderate electric field was investigated as well as with theoretical calculations of dependence $T_e(E)$.

The electric field dependencies of the change of absorption coefficient for s- and p-polarizations of submillimeter radiation are also studied. Comparison of experimental and calculated data for light absorption at different electron temperatures is carried out.

Acknowledgments

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References

[1] J. Faist, F. Capasso, D. L. Sivco et al. *Science* **264** 553 (1994).
[2] O. Gauthier-Lafaye, S. Sauvage, P. Boucaud et al. *Appl. Phys. Lett.* **70** 3197 (1997).
[3] E. Gornick, R. Schawarz, D. C. Tsui et al. *Solid State Commun.* **38** 541 (1981).
[4] L. E. Vorobjev, D. V. Donetsky, L. E. Golub. *JETP Lett.* **63** 977 (1996).
[5] V. Ya. Aleshkin, A. A. Andronov et al. *Physica Status Sol.* (b) **204** 173 (1997); **204** 563 (1997).
[6] H. Sakaki, T. Noda, K. Hirakawa et. al. *Appl. Phys. Lett.* **51** 1934 (1987).
[7] L. E. Vorobjev, D. V. Donetsky, A. Kastalsky. *Semiconductors* **29** 924 (1995).
[8] K. Hirakawa, M. Grayson, D. C. Tsui et al. *Phys. Rev.* **B 47** 16651 (1993).